SUPERCONDUCTING MAGNET SYSTEMS AT FERMILAB*

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ABSTRACT

The present state of superconducting magnet technology at Fermilab is shown by examples of superconducting magnets being used as High Energy Physics experimental equipment. A very large bubble chamber magnet and several large dipole magnets have been built and all are being used as power savers. Simple economics justifies the construction of such magnets. Initial capital costs are about the same, but operational costs are not. Well-designed superconducting magnets cost much less to operate than conventional magnets. Future superconducting magnet systems now being studied and developed are also described.

I. INTRODUCTION

For many years the high-energy physics community has recognized the potential of superconducting magnets. In fact, to date the strongest single driving force pressing the development of superconducting magnets can probably be attributed to members of this community. High Energy Physicists are accustomed to dealing with new ideas and the development of whatever is needed to investigate their new ideas.

Fermi National Accelerator Laboratory has been actively pursuing the application of superconducting magnets since the founding of the laboratory. During the early stages of accelerator design the possibility of using superconducting magnets as accelerator components was studied and rejected. The art of building such magnets was not then sufficiently advanced for us to gamble on them. At that time it was decided to advance the development of superconducting magnet systems with the idea of introducing such magnets into our program when the gambling odds were better identified.

Since that time three independent efforts have been pursued. The first effort was the design and construction of a large bubble chamber magnet using superconducting coils. Several papers describing design and construction of this bubble chamber have been presented elsewhere.[1] I will describe the magnet briefly and move on to operational performance which has not been treated previously.

The second effort is a continuing program[2] to build large superconducting dipole magnets which are used as experimental equipment. These particle analysis magnets are much cheaper to operate than conventional magnets and they are gaining popularity at Fermilab. The experimenter at Fermilab no longer feels that the success of his experiment is being gambled if a superconducting magnet is assigned to his experiment. The overall success of this program justifies detailed discussion about the engineering concept and operational experience.

The last effort is a combination of two related projects. The long range goals of both efforts deal with increasing the energy output of our accelerator. The original commitment of our laboratory was to build a machine which would accelerate protons to 200 GeV. Accelerator design progressed with this commitment as a short range goal only, with plans to upgrade performance to higher energies as soon as possible. To date the accelerator has operated at energies greater than 400 GeV and we will continue to press to higher energies. If we can build high field superconducting magnets, energies of 1000 GeV can be achieved without increasing electrical power consumption.

Progress in the development of pulsed superconducting magnets has been reported at conferences for many years.[3,4,5] Parallel development efforts at several laboratories have advanced the technology, and prototype dipole and quadrupole magnets have been built and tested. These development results indicate that superconducting synchrotron accelerator magnets are "within reach" and we hope to use such magnets as soon as possible. The gambling odds are much more favorable today with most of the problems identified and solved. The few remaining problem areas which are not completely understood should be resolved in the near future and a fourth acceleration stage will be added to the machine. The existing third stage is a ring of conventional magnets one km in radius and the new fourth stage (energy doubler/saver) will be the same diameter located inside the existing third stage tunnel. The present development status of magnets and helium cooling system is reported.

In conjunction with the energy doubler effort, we started the development of beam transport magnets. When we upgrade the accelerator to higher energies, we must also upgrade the magnet systems which transport beam from accelerator to experimental areas. These magnets will be similar to energy doubler magnets in concept and differ only in aperture size and pulsing is not required.

II. LARGE DIPOLE PROGRAM

Background

Our small group entered into the superconducting magnet field in the late 1960's and the outlook was very optimistic. At that time it appeared that all of the big problems had been solved. Superconducting wire was available to meet whatever our needs might be. Wire manufacturers promised long lengths of superconducting wire with continuous NbTi filaments well bonded to the Cu matrix and twisted for stable performance. All that was left to the magnet builder was to wind the wire into a suitable coil shape and to arrange for cooling the wire. We then asked ourselves the following questions:

1. Why are so many people with experience in the field still finding difficulty with unstable coil performance?

2. What are the differences between the types of coils that exhibit training and those that do not train?

3. What must we do to build a superconducting magnet that never quenches?

4. How can we use existing knowledge to contribute to our laboratory in short order and further superconductivity long range?

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5. Which type of magnet should we concentrate upon as a first effort? We wanted to force superconductivity out of the research lab and into the field as soon as possible to demonstrate that such magnets are useful.

After much searching and discussion with respect to the above questions, we concluded the following:

1. Coil stability is dominated by conductor temperature. Most of the successful magnet projects used a coil type construction with good conductor to coolant heat transfer.

2. If we maximize the coil conductor surface area in direct contact with the helium coolant we should be able to build coils that never quench. We made no attempt to solve the training problem; we by-passed the problem and accomplished stability by overcooling the conductor.

3. Our first efforts would be to build full scale dipole and quadrupole magnets at 1.8 Tesla which could be substituted for existing conventional magnets.

Within two years we succeeded in accomplishing our goals. A 3 meter dipole with a 4 x 10 cm bore was built and operated without difficulty. A 3 meter quadrupole with a 10 cm bore diameter followed with similar results and we were pleased with the success of our first effort. Both coils were wound with small diameter round wire with the conductors spaced such that the helium coolant was in direct contact with the conductor surface. The coils were clamped directly to the field shaping iron with tie studs and the magnet assembly (coil and iron) was enclosed with a stainless steel helium vessel shell.

This straightforward engineering approach provided superconducting substitutes for conventional d.c. beam transport magnets. We then proceeded to the logical second stage of identifying some length of beam transport system that was still on the drawing board where we could switch magnets. To our dismay, we could not sell our replacement scheme to laboratory management and a valuable lesson had been learned. Applied superconductivity was still looked upon as a new technology and as such it was considered a high risk gamble. Also, unsuccessful development efforts of the past had given the technology a "long shot" reputation. If we were going to sell superconducting magnets we would have to entice the user by promising results far exceeding that which he could achieve using the well established conventional technology.

Following our first set-back, we re-aligned our thinking in preparation for a second attack. We asked ourselves, "What are the salient features of the devices we have thus far developed and how can we further exploit them?". After some thought we decided that our best strategy would be to challenge conventional magnets where we had the advantage. The original electrical power consumption estimates for the Laboratory were based upon accelerator operation at 200 GeV. With accelerator output being pushed to 400 GeV and higher, electrical power consumption was destined to become a serious problem. With this foresight we then established a new goal of building superconducting power savers. We then set out to identify a group of conventional magnets that we might convert to efficient superconducting magnets.

Program Goals

We soon found an ideal candidate to challenge. Many high-energy physics experiments use large dipole magnets as spectrometers downstream from the target. These magnets operate in the steady state d.c. condition consuming large amounts of electrical power. Furthermore, with higher beam energies available to the experimenter, even larger particle analysis magnets would be needed. Future particle analysis magnets should become efficient superconducting magnets.

The first phase of the new program was to develop a superconducting magnet which would be the equivalent of an existing particle analysis magnet. We decided to make the superconducting prototype the same size as the conventional magnet to avoid scaling problems. The primary goals of the project were then defined as follows:

COST - initial capital cost about the same as the conventional version.

RELIABILITY - no more "down time" than the conventional magnet.

EFFICIENCY - overall power consumption for continuous operation less than 10% of the conventional magnet.

The first two goals reflect the general attitude of the project. We were not out to beat conventional magnets with respect to cost and reliability. To match cost and reliability is ambitious enough and it can be done. However, we had a definite advantage with respect to operational cost and we were out to win.

Engineering Concept

To achieve the above goals the concept evolved to the following design considerations:

1. The dominant operating cost for most superconducting magnets is the power used to reliquify the boil-off helium coolant. Heat transfer into the liquid helium environment must be reduced to a minimum without sacrificing reliability or cost.

2. The current path connecting the power supply to the coil is a major heat leak. This loss can be eliminated by operating the coil in persistent mode with current leads removed or reduced to a low level by using a flux pump. However, both of these methods are more complicated than a vapor-cooled current lead system. Therefore, vapor-cooled leads were chosen for reliability but low currents are used to reduce current lead losses to an acceptable level.

3. The room temperature to low temperature support structure heat leak must be reduced to a minimum. Thermal isolation of the low temperature region is improved if the electromagnetic forces developed in the coil can be carried by the helium vessel. The support system design loads are then reduced to dead weight and unbalanced magnetic forces due to misalignment between coil and iron. For example, our support system contributes less than 10% to the total heat leak.

4. With good design and careful construction, heat leak through the insulating vacuum can be reduced to a low level. For example, efficient liquid helium storage dewars have been available for many years. The same techniques can be applied to the construction of superconducting magnet cryostats.

5. If liquid helium consumption can be reduced to a low level, the helium vessel can be sized to

store enough liquid helium above the coil so that the time period between liquid helium refills becomes long. A periodic refill system of supplying liquid helium to the magnet can then be used and the cost and complication of including a helium refrigerator as part of the magnet system is eliminated.

6. The vapor-cooled current lead should be the only helium vessel outlet and all exiting vapor flows through that outlet. Even during helium fill operations, the exiting vapor assures current lead cooling.

7. With good welding, the cryopumping capability of the helium vessel walls should maintain insulating vacuum integrity indefinitely, i.e., continuous pumping with a vacuum pump is not required and system reliability is improved.

8. A liquid nitrogen cooled radiation shield is used. The liquid nitrogen storage volume is sized so that the time period between refills is the same as the helium system.

Coil Design and Construction

Superconducting coil design criteria is by far the most difficult series of decisions that the magnet builder must face. Common terminology in the field such as: current density, copper to superconductor ratio, residual resistivity ratio, surface heat transfer flux, training and various stability criteria are tossed about with ease by the prototype-oriented researcher. All of these terms have definite meaning but the "trade off" between terms may not be so well understood when coil design decisions must be made. I feel that the research prototype decisions deal with "How adventurous do I feel" while the project engineer addresses the same decisions with "How adventurous must I be."

The decisions made with respect to our coil design could best be described as "Not very adventurous but sound engineering". Our primary goal was to build useful power savers as soon as possible and the coil must perform properly.

The decision to use small diameter round wire was based upon the following straightforward approach. If we assume that a fixed volume of conductor of variable cross sectional area will be used to build a known size coil and the number of ampere turns is fixed, the heat generated due to electrical losses in the copper during the charge and discharge transients also remains constant. To restate in straightforward engineering language; if we neglect secondary effects, heat generation in the coil is independent of the conductor size. However, heat transfer between the conductor and coolant is a function of conductor size since it is directly related to the conductor surface area exposed to liquid helium. Therefore, we can express coil cooling capability with respect to conductor size as:

$$\text{Cooling capability} = \frac{\dot{Q}_{cooling}}{\dot{Q}_{heating}} = f\left(\frac{1}{d}\right) = f\left(n^{\frac{1}{2}}\right)$$

where $\dot{Q}_{cooling}$ = coil surface cooling rate

$\dot{Q}_{heating}$ = coil heat generation rate

d = conductor cross-sectional dimension (diameter for round wire)

n = number of coil turns

This expression shows that a coil construction which uses many turns of small wire to develop the required number of ampere turns has good cooling capability. Also, current lead losses suggest that small wire would be a wise decision. For our application a large coil inductance was not a severe constraint with magnet charge and discharge time periods of several hours acceptable to the experimenter. An operating current of approximately 200 amps was chosen which led to a conductor size of less than 2 mm diameter.

Coil construction is shown in figure 1. Coils

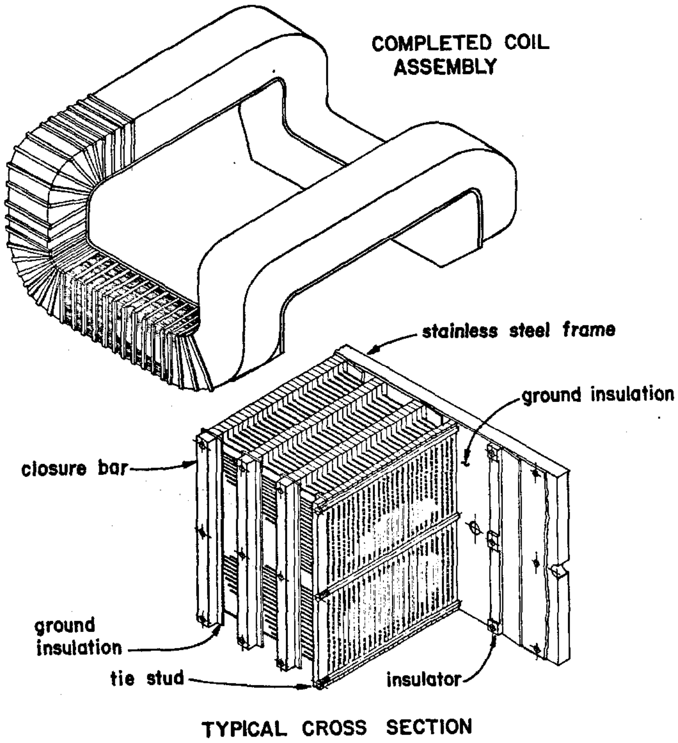

Fig. 1 Coil Construction

are wound on a saddle-shaped stainless steel frame using round wire and epoxy glass laminate layer spacing insulators which are located approximately 5 cm center to center. The insulators also serve as layer clamping members and remain as part of the coil assembly. In this manner, the wire remains tightly clamped as we progress from layer to layer. The coil assembly is saddle-shaped and rectangular in cross section with 3 tie studs clamping each stack of layer spacing insulators directly to the steel frame. After the coil is wound, stainless steel closure bars are installed and all tie studs are torqued. Some of the advantages of this type of construction are:

1. Small diameter wire is easy to wind.

2. The coil structure is well defined and readily analyzed, i.e., the insulators are the load bearing members which transmit the electromagnetic forces through the coil structure. Individual conductors are treated analytically as a continuous beam on multiple supports

3. Liquid helium contacts all wire surfaces which enhances coil stability.

4. Layer to layer shorts are almost impossible with a spacing of 2 or 3 wire diameters between layers. Insulator thickness (layer spacing) is governed by the insulator stiffness required to keep the coil tightly clamped during winding.

5. If the wire electrical insulation is damaged, turn to turn shorts do not present a problem since the turn to turn voltage drop is so small.

6. Coil to ground insulation is easily installed.

7. The thermal contraction of the composite coil assembly may be designed to match the stainless steel frame and helium shell as closely as required.

Shell Construction

The helium vessel is made from stainless steel plate and assembled around the coil as shown in figure 2. The coil is attached to the vessel wall

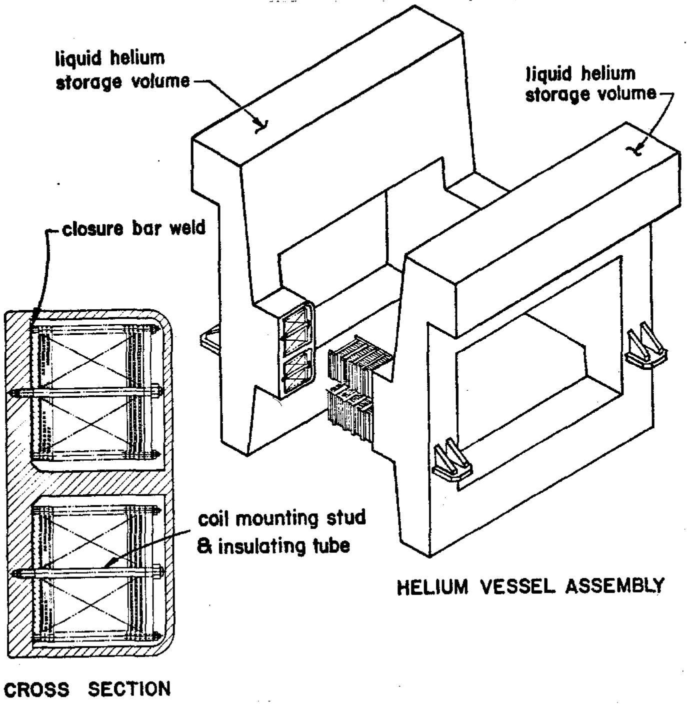

Fig. 2 Helium Vessel

with mounting studs as shown. All mounting studs are insulated from the coil by cylindrical insulators which slip over the stud after the stud is threaded into the shell wall. The coil to shell mounting studs are then torqued and the coil closure bars are welded to the shell wall as shown. The remaining plates are then added and the helium vessel welding is completed.

The liquid nitrogen vessels and vessel supports are made of stainless steel plate and the remaining shell is made of thin copper sheets as shown in figure 3. The radiation shield is fabricated using threaded fasteners and then disassembled and reassembled around the helium vessel. Coolant tubes are soft-soldered to the Cu shield with all tubes sloping up toward the vessels. Nitrogen vapor generated inside the coolant tubes then flows up the coolant tube into the vessel ullage space. Both liquid nitrogen storage vessels are vented by overflow tubes.

The outermost shell (vacuum jacket) is made of mild steel and/or stainless steel. The shell is made up as several weld subassemblies which are then assembled around the nitrogen shield as shown in figure 4. Two of the support columns[6] are also shown. All four columns use flexual hinges both top and bottom to compensate for differential contraction between the helium vessel and outer shell. The radiation shield is

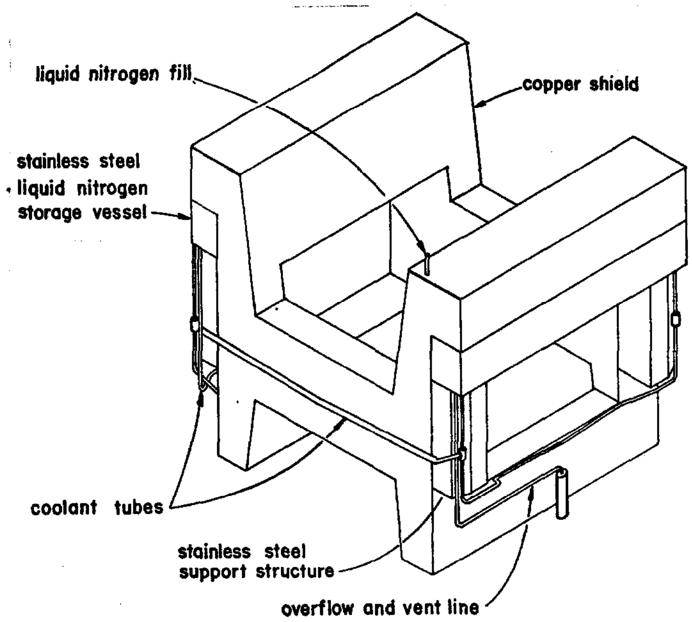

Fig. 3 Radiation Shield

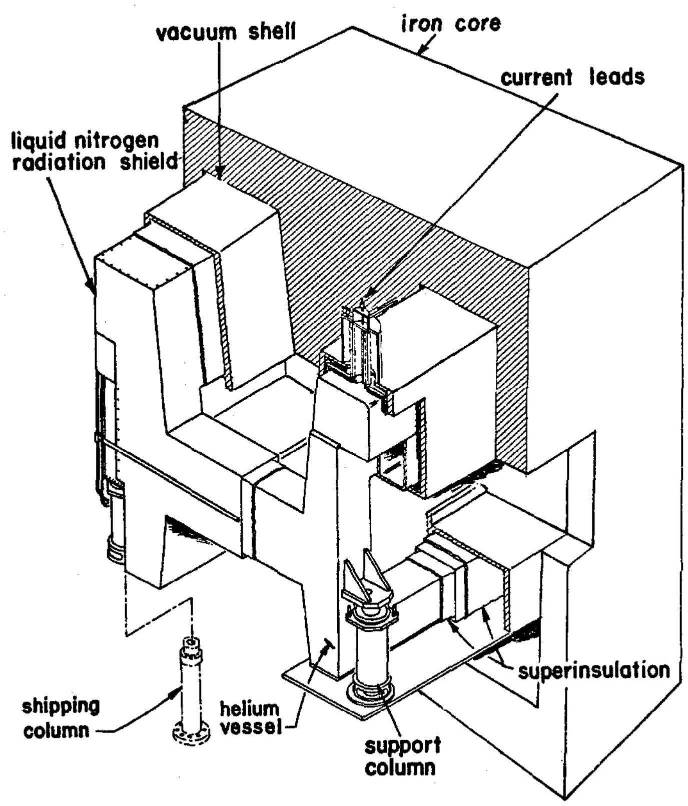

Fig. 4 Magnet Assembly

also supported by these support columns as shown. Four steel shipping columns are installed inside the support columns when the magnet is being transported.

Magnet Assembly

The complete magnet is shown in figure 4. Large blocks of iron are stacked around the cryostat and bolted together. The shipping columns are then removed and super insulation is inserted into the column cavities to decrease radiation losses. The column access covers are then reinstalled and the insulating vacuum is "pumped down". The bolts securing the column access covers are then removed and replaced with set screws. These access covers then function as blow off covers and serve as a pressure relief system.

Magnet Operation

All magnets are designed to operate continuously with helium and nitrogen refills once per week. Magnet size and operating data range as shown below.

field volume	.4-1.6	Tesla meters cubed
total weight	65-165	metric tons
stored energy	300-2000	kilojoules
full field	1.8-2.0	Tesla
operating current	200	amperes d.c.
nitrogen storage	170-250	liquid liters
nitrogen use rate	18-30	liters per day
helium storage	500-600	liquid liters
helium use rate	36-50	liters per day

To date four of these magnets have been built and are presently being used in Fermilab experiments. All of these magnets operate reliably and efficiently without special attention. Several more are in the design and construction stages and many more are planned for the future.

Future Plans

The concept described herein will be used to build future magnets with engineering refinements leading to better efficiencies and further power savings. By using superconducting coils in place of conventional copper coils, operating costs can be reduced significantly. For our application which uses large magnets operating in the steady state d.c. condition, operating cost reductions of more than 99% can be achieved.

This gain in operating efficiency has been accomplished without sacrificing initial capital cost. The total cost of superconducting magnet and magnet-related system is comparable to an equivalent conventional magnet system. With good design and careful construction, superconducting magnet systems can be built which operate reliably and efficiently with no more "down time" than a conventional system.

III. BUBBLE CHAMBER MAGNET

Design Background

The Fermilab bubble chamber magnet design was started in June, 1970. The primary design aim was to achieve the most economical design and construction without sacrificing safety and reliability. Superconducting coils had been used in other bubble chambers and the same arguments hold for incorporating superconducting coils into our design. For large bubble chambers the initial capital cost of a superconducting magnet system is somewhat less than the cost of an equivalent conventional magnet system, but the real savings are associated with long term operation. For continuous operation, the overall power consumption of an efficient superconducting magnet is less than 1% of the electrical power demanded by a comparable conventional magnet. If our bubble chamber magnet had been built using conventional coils, the electrical power consumption would be about equal to the accelerator.

Argonne National Laboratory agreed to design and fabricate the large solenoid coils and shells based upon their previous experience with the Argonne 12-foot bubble chamber. All of the design decisions were based upon a minimum amount of development testing with proven design and construction methods to be used as much as possible. We feel that our design represents a good compromise of what could be learned from other bubble chamber magnet builders plus additional engineering refinements based upon recent developments in superconducting magnet technology. The magnet design data is shown in Table 1.

TABLE 1

Magnet Parameters

Winding inside diameter	4.27 m
Winding outside diameter	5.08 m
Spacing between coils	99 cm
Length of bottom coil	97 cm
Length of top coil	93 cm
No. of pancakes bottom coil	22
No. of pancakes top coil	21
No. of turns per pancake (average)	65
Total number of turns	2860
Length of conductor per pancake (average)	950 m
Total length of conductor	40.8 km
Weight of conductor	50 Tons
Weight of stainless steel strip	23.6 Tons
Operating current	5000 A
Ampere turns	14.3×10^6
Current density in conductor	3700 A/cm^2
Average current density	1885 A/cm^2
Central field	3.01 T
Maximum axial field	5.14 T
Maximum radial field	4.01 T
Self-inductance	31.7 H
Stored energy	396 MJ

Construction and Operation

The magnet was final assembled at the bubble chamber facility, but independent of chamber construction. The completed magnet was then moved as a single unit to the chamber construction area, placed into final position and prepared for operation. The magnet/bubble chamber cross section is shown in figure 5.

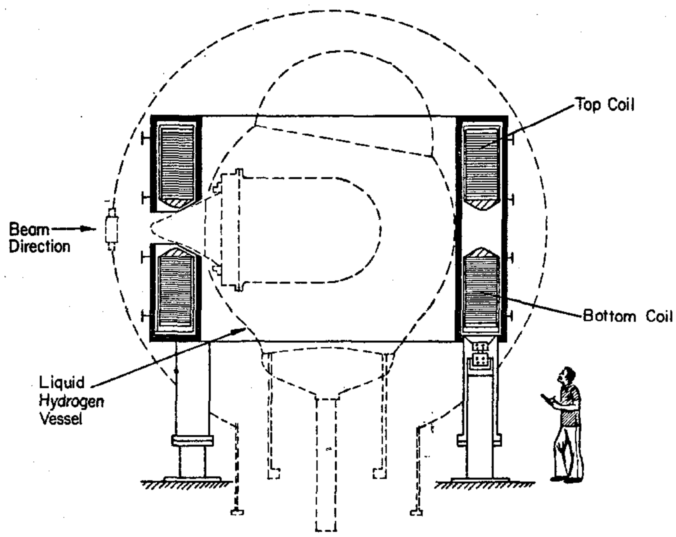

Fig. 5 Magnet/Bubble Chamber Cross Section

The particle beam enters the 30,000 liter liquid hydrogen volume through the snout at the left.

The first magnet cool down was accomplished with minor "first time" problems only and the coils were energized for the first time in August 1972 just 26 months after start of design. Magnet operation can best be described as most successful. The magnet was charged to full field within 24 hours without difficulty. The operational helium boil-off of 55 liquid liters of helium per hour was in good agreement with the calculated heat leak.

To date the magnet has been operated for approximately 10,000 hours with no major problems. The charge and discharge time period is 5 hours with weekly charge and discharge performed for normal maintenance. Our operational experience thus far can be summarized as follows:

1. A well designed superconducting magnet system is much more reliable than some of the other bubble chamber sub-systems.

2. The advantages of an iron-free magnet outweigh the disadvantages. The overall design is much simpler and easy access to the chamber decreases maintenance and repair time. With proper planning, stray fields do not present a serious problem. Most of the equipment seriously affected by magnetic fields can be located outside the stray field area and those which must be within the high field region can be shielded.

3. Most magnet system problems are coolant system related with liquifier expansion engine seals being the weakest link.

4. Coolant system reliability improves with operational experience but the learning time period may be longer than expected.

5. Contaminated helium may cause refrigerator problems on start up but the coolant "cleans up" with extended operation.

6. A helium liquifier system that uses a large storage dewar to supply liquid helium to the magnet is a good method of limiting magnet system "down time". The larger the dewar the longer the time periods available for liquifier maintenance and repairs.

IV. ENERGY DOUBLER/SAVER MAGNETS

The Fermilab energy doubler program was initiated in 1972 as an "all out" effort. The initial thrust of the project was divided into two primary efforts (1) the development of a helium coolant system and (2) the study and development of high field (approximately 4.5 Tesla) pulsed superconducting magnets. The coolant system development results are documented elsewhere.[7] We do not anticipate serious difficulty in cooling over 6 km of superconducting magnets. Prototype performance test results indicate that the superconducting filaments can be maintained at temperatures less than 5°K. The helium circulation system is shown schematically in figure 6. A helium liquifier supplies liquid helium to a large storage dewar. A circulation pump, located in the bottom of the dewar, drives the subcooled liquid through some length of magnets (120 m minimum). The helium coolant then flows through the coil structure absorbing heat generated by the coils. The coolant exits the coils as subcooled liquid and flows to the end of the line where an expansion valve reduces the coolant temperature and pressure to saturation. The coolant then flows back down the line around the outside of the coil vessel shells as two phase helium and returns to the storage dewar. The radiation and support structure heat load is intercepted by the return flow.

The magnet development effort started off with much enthusiasm and success did not seem too far distant. Similar efforts at other laboratories had been fairly successful and we wanted to supplement their developments with new ideas directed toward mass production of many identical magnets. The following ground rules were then established:

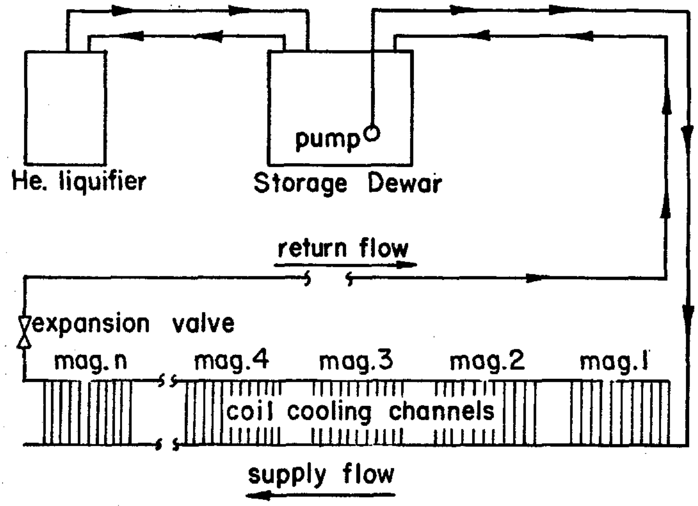

Fig. 6 Helium Circulation System

1. Doubler cycle time will be about one minute.

2. The magnet cryostats will serve as coolant transfer lines, i.e., no external liquid helium transfer lines will be required.

3. The magnets will have a cold beam tube.

4. The magnet enhancement iron will be at room temperature and non-saturating. These criteria will provide magnets whose fields are linear with excitation and small in cross sectional area. The small thermal mass reduces the cool down time period and the amount of refrigeration needed.

5. The superconducting material will be NbTi.

6. The current in the conductor will be consistent with utilization of existing main accelerator power supplies.

To date, the coil design has evolved to a double shell type construction. A typical cross-section is shown in figure 7. The shell pairs are surface cooled

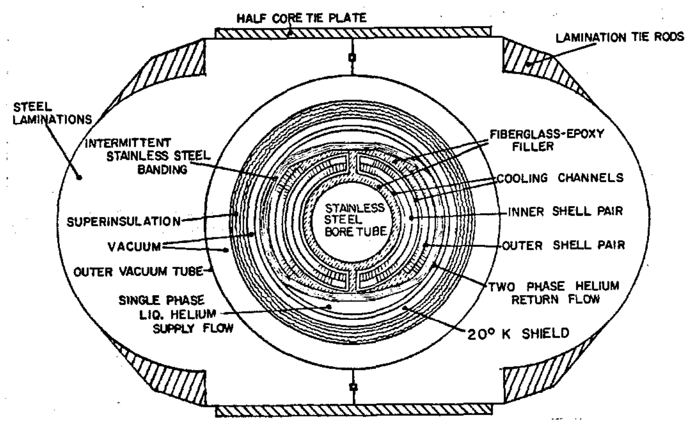

Fig. 7 Dipole Cross Section With 7.5 cm. Diameter Bore

with approximately 40% of the conductor surface area exposed to liquid helium.

The dominant problem which has not yet been resolved is the problem of premature quenching. Many prototype coils have been built and tested with some insight gained about the nature of training. However, the detailed mechanism is not yet fully understood.

The cause of this undesirable effect (training) has been studied by a number of investigators with the following conclusions:

1. Training is due to an unidentified mechanical loss.

2. The source of this mechanical loss may be friction heating associated with relative motion between adjacent conductors or displacements of coil relative to boundaries.

3. The source of this mechanical loss may be the sudden release of strain energy associated with fracture of the bonding material (epoxy or equivalent) used to impregnate the coil.[8]

4. The source of this mechanical loss may be inelastic behavior of the NbTi[9] or the copper matrix[10] used to stabilize the superconductor.

All three of these theories have merit and the final analysis may show that all contribute with the dominant one related to the type of coil structure chosen. Further studies of the mechanical losses that cause unstable superconducting coil performance should lead to a better understanding of how to build superconducting coils. With this new knowledge, stable coils will be built and the energy doubler/saver program will move on toward completion.

V. CONCLUSION

Superconducting magnet systems have found application at Fermilab and a look to the future shows much broader application. Two projects have successfully shown that significant power savings can be gained by using superconducting coils in place of conventional copper coils. For large magnets operating in the steady state d.c. condition, operating cost reductions of more than 99% can be achieved.

The energy doubler/saver program has also investigated the electrical power savings potential of superconducting magnets. If superconducting magnets could be used in conjunction with our present main ring magnets, we could operate at 400 GeV and reduce accelerator power consumption by more than 50%

This power saving potential of superconducting magnets justifies additional development at Fermilab and elsewhere.

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